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Refugee housing through cyclic design

Daniel Fosas ^a , Dima Albadra ^a , Sukumar Natarajan ^a , David A. Coley ^{a*} 

^a *Department of Architecture and Civil Engineering, University of Bath, Bath, UK*

*Contact: d.a.coley@bath.ac.uk

There are more than six million refugees living in camps globally, primarily in places with severe climates. While camps are planned to be temporary, they can be in use for decades. This “planned temporariness”, despite their potential longevity, together with the pressures of rapidly emerging situations, means the construction and monitoring of demonstrators is not a primary concern for their developers. This lack of iterative design improvement results in shelters with thermal environments far from ideal and a risk of increased morbidity. Here we propose a cyclical process for improving such shelters involving the thermal monitoring of pre-existing shelters to construct validated baseline simulation models of similar shelters in other areas of emerging crisis. These models can then be evolved and improved within an optimisation cycle before mass-construction and field testing. Here we demonstrate the method for the case of Azraq camp in Jordan. Starting from an analysis of field survey data which exposes a high incidence of heat-stress experienced in the shelters, a series of architectural strategies are applied to the design, resulting in significant reductions in overheating. This work suggests that the proposed cyclical approach can lead to significant improvement in conditions currently experienced in refugee camp shelters.

Keywords: shelters, overheating, passive architecture, building simulation, thermal comfort, cyclic design

1 Introduction

Current figures of forcibly displaced populations in the world are among the highest on record, of which 37% (25.4 million) are refugees (UNHCR 2018a). As part of the response to the crisis behind these figures, refugees are often hosted in camps and the humanitarian agencies behind them face the challenging task of providing *a housing solution* to an unexpected crisis of unknown duration. However, due to a number of factors that arise in the decision-making process of the design of these camps, solutions tend to be temporary in nature. Given that many of these camps often exceed their expected lifetime and that humanitarian agencies are already under extreme pressure in rapidly emerging situations, little attention tends to be paid to the thermal adequacy of indoor environments in these shelters. Focusing on this aspect of shelter provision for refugees, we give an overview of how refugee housing is currently addressed, highlighting gaps and opportunities that exist for the application of sound passive design principles via a cyclical design process to mitigate thermal conditions at the extremes.

1.1 Background

Refugees and forcibly displaced people fall under the mandate of the UNHCR, the United Nations refugee agency. UNHCR is the main provider of assistance to host countries at the request of their governments or the UN Secretary General. In addition, the UNHCR has several operational partners such as non-governmental organisations (NGOs) who act along with the UNHCR at the local level in so-called ‘clusters’. In terms of shelter provision in refugee camps, the UNHCR is the cluster leader (UNHCR 2007). More often than not, the UNHCR and its operational partners have very limited time to propose shelter solutions suitable for the situation at hand. Therefore, it is often the case that the refugees are initially housed in tents before other options are proposed.

As such, provision of those shelters usually occurs in following stages: emergency, temporary or transitional and permanent (Félix, Branco, and Feio 2013). In general, host governments are resistant to permanency and tend to encourage shelter solutions that are temporary in nature, dismantlable and made of lightweight materials. This means that refugees can end up living in temporary shelters for several years, sometimes even decades.

Understandably, the shelter design focus is generally on transportability and deployability of shelters, but despite the numerous attempts to design new shelter solutions, their thermal performance is still largely overlooked (Albadra, Coley, and Hart 2018). Moreover, other aspects related to indoor environmental quality such as visual and acoustic performance, as well as social and cultural factors, are often neglected despite their acknowledged importance. Even available standards and guidelines for temporary shelter design are generic when it comes to climatic and cultural considerations and those that do, focus mostly on ‘winterisation’ (UNHCR 2007; The Sphere project 2011; Corsellis 2012). This results in an underdeveloped area of research considering the number of people involved and the potential risks associated.

1.2 Cyclic design

We argue that within the procurement process for such shelters, the inclusion of a holistic appraisal system evaluating the relative merits of a range of low-cost passive techniques could be transformative, particularly in hot climates where, to-date, they have received relatively little attention. Since current shelter provision procedures involve complex decision-making often involving different agencies, we hypothesize that many key lessons that could aid in the development of shelters with improved thermal performance are being overlooked.

To mitigate this, we propose a ‘cyclic design’ process in which

- a) refugee camps are surveyed to understand the possible shortcomings of the shelters in place;
- b) optimization simulations are undertaken to mitigate against the revealed flaws and to explore best fit solutions to maximally improve the thermal performance of the shelters at acceptable costs to the agencies involved;
- c) demonstrator shelters are erected in the camps and monitored to validate the model findings and
- d) the process begins again at (a) at the next camp (or next iteration of shelters at the same camp) using the knowledge gained.

The advantage of such an approach is that it can be undertaken within the current ‘planned temporariness’ paradigm of camp design while building on a progressively developing local expertise across several verticals such as supply network, materials, and construction techniques.

1.3 Objectives

Our main objective is to use the large refugee camp of Azraq in Jordan as a case study of how a cyclical design process can be applied to improve shelter design, particularly with respect to overheating and heat stress. Jordan is chosen as an ideal case study as it provides all the key features of the current challenges facing refugee shelter design globally:

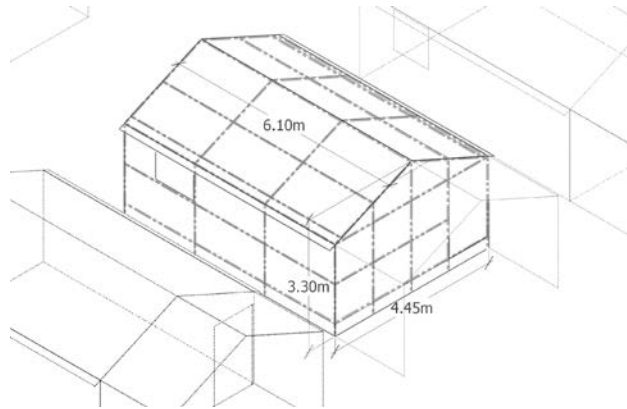
- the influx of a large number of refugees over a very short period (2014 onwards) in contrast to other camps (e.g. those on the West Bank) where the process of camp building has occurred over several decades;
- its extreme climate with both hot (day) and cold (night) extremes, though our focus is primarily on the former; and

- the delicate socio-political conditions that limit designers from developing solutions that either are, or appear to be, permanent in nature.

The paper describes the housing context of the study camp and explores the challenges faced by camp residents and authorities. Then, the annual overheating evaluation methods used to measure the performance of shelters and the predicted impacts on occupants are described. The following two sections then present the results of applying the method for the case study, one for the original shelters and another incorporating the potential design improvements informed by the field work. Finally, the findings and the limitations of the study are discussed and its implications for future research are summarised.

2 Housing context: desert refugee camp

The case study is located in the Azraq refugee camp in Jordan at an elevation of around 700m above sea level, established as part of the regional response to the Syrian crisis that began in 2011. Located at 31.90°N 36.58°W, the camp is exposed to a hot desert climate (Kottek and J Grieser 2006). As of June 2018, there were 40,092 persons of concern here, with 59% of the population under 18 years old, 2% above 59 years old and an equal gender split (UNHCR 2018b). Nearly 9,000 transitional shelters house the population at the moment, all of which are based on the same design (Figure 1).



a) Overview (interlocking steel structure superimposed)



b) Example of shelter interior

Figure 1: Transitional shelter at Azraq refugee camp

Azraq camp was pre-planned, on a site that had been developed in the 1990s to accommodate Iraqi refugees. As the war in Syria intensified and Zaatari camp in Jordan reached its full capacity, over 13,000 transitional shelters were planned in Azraq in preparation for a new influx of refugees in 2014 (IFRC, UN-Habitat, and UNHCR 2014). The shelter was designed by UNHCR and structural safety, protection from the elements, speed of construction and use of local materials were all factors considered in the selection process (IFRC, UN-Habitat, and UNHCR 2014). At a later stage, kitchen extensions were built and the whole of Azraq camp was connected to an electricity grid by the end of 2017, among other improvements (UNHCR 2018b).

The following sections introduce the climate at this location and the field study conducted. The first helps to understand challenges and opportunities for passive architecture and the second characterizes the housing conditions.

2.1 *Climate overview*

To ease the interpretation of results in this study, the climate at Azraq is considered through the weather file used in the simulation method presented in 3.1. Temperatures are within comfortable ranges for 37% of the time and the average temperature is 20 °C,

with minimums below 0 °C and peak temperatures surpassing 43 °C (Figure 7-a). The difference between the maximum and minimum temperature over a day is, on average, 12 °C and days are typically sunny, with clear skies at night, consistent with the expectations for a hot desert climate.

2.2 *Field studies: lessons learned*

Field studies were carried out in summer 2016 and winter 2017 to examine the thermal performance of the shelters, evaluate residents' thermal satisfaction and understand camp development dynamics (for an explanation of materials and methods of the field studies referenced in this section see Albadra et al. 2017).

Spot surface temperature measurements, air temperature and relative humidity were taken in 38 shelters between 09:00 and 15:00, from 31st August to 23rd September 2016. A weather station located on a tripod 2.5 m high on the roof of UNHCR office caravan at the nearby Zaatari camp provided concurrent external weather data. The monitoring was limited to these periods and methods due to political and other sensitivities. Thus, whole-, or multi-year monitoring of occupied shelters was not possible.

Camp residents ($n = 84$) were interviewed and confirmed that overheating inside the shelters was a problem. The analysis of the thermal survey completed by randomly selected families indicated a comfortable temperature band between 17.2 °C and 28.4 °C (i.e. thermal sensation votes between ± 1 , 80% acceptability). The social survey focused on factors such as perceived security, privacy or adaptation opportunities. The main cooling strategy at shelter level was found to be natural ventilation and reported coping mechanisms against heat were mainly to pour water onto themselves with their clothes on and to spray water on the floor (Albadra et al., 2017). However, more recent improvements in electricity supply has allowed the use of

fans (UNHCR 2018b). Lastly, shelter units were documented ‘as built’ to track any discrepancies between the original specification and their actual conditions as discussed in 3.1 and 4.1 below.

Based on these findings, UNHCR Jordan welcomed further collaborations to understand and quantify annual overheating in these shelters and, if need be, to suggest design upgrades. Should overheating mitigation measures be needed, their scope should be restricted to the shelters themselves because, due to security concerns - among other considerations - the structure of the camp cannot be modified. In addition, they were requested not to have a significant impact on the original structure and to keep fundamentally the same external appearance.

3 Overheating evaluation methods

Owing to the impossibility of determining annual overheating empirically for a wide range of potential solutions, simulation was used to find the likely thermal conditions in the shelters, and estimate the likely occupant perception over the year. Here, these are addressed with two types of heat and mass transfer simulations, the simulation of the shelter on one side via building physics, and the simulation of occupants via human thermal models on the other. The former depicts the indoor thermal environment given descriptions of the weather, shelter structure and occupant behaviour. The second uses a model to evaluate that computed indoor thermal environment and information about the occupants to estimate how they perceive or react to such conditions. These simulations, although tightly coupled, are considered here different and, to a certain extent, independent. Thus, they are introduced separately in the following.

3.1 Shelter thermal model

A shelter model was created based on the original design specifications (UNHCR 2016) in EnergyPlus v8.9 (NREL 2018; Crawley et al. 2001). The approach is the creation of a ‘reasonable model template’ that is later informed by the field study findings and validated against collected data, and eventually upgraded with potential overheating countermeasures.

The simulation relies on the weather description provided by a ‘typical year’ selection algorithm (Herrera et al. 2017) for the nearest available location under the same climate (Safawi, 60 km North-West from Azraq (Meteonorm 2018)), meaning that months in historical data are selected to create a composite year that aims to represent the average weather conditions (approximating the Test Reference Year method (NCDC 1976)). A difficulty found in the context of refugee housing is the scarcity of readily and publicly available weather files. Refugee camps can be located at considerable distances from weather stations with complete and long-term records. It must be noted that the weather file previously mentioned combines observed weather data and modelled weather data — mainly solar radiation and cloud cover — to create complete hourly records (Meteonorm 2017).

The shelter is surrounded by other units, following the regular grid of the camp. Surrounding shelters provide basic shading and solar radiation reflections are accounted for. They also limit the windspeed for natural ventilation, roughly approximated as the wind profile of an urban environment as a worst-case scenario (ASHRAE 2017).

The shelter is considered in its original form but with the shading upgrade on the front façade (i.e. that with the door, Figure 1). Viewed from the outside, the walls are made of Inverted Box Rib (IBR) panels, 15mm foam insulation covered with aluminium foil, 60 mm cavity created by interlocking steel structure, and an internal IBR panel.

The roof follows a similar arrangement except for the internal IBR panel, substituted by tarp-like materials. The floor is a 10 cm concrete ground slab, modelled through the F-value method (Baylon and Kennedy 2007; ANSI/ASHRAE 2009).

Internal gains are mainly limited to occupancy, typically up to 6 persons per unit, two adults and four children, and small electrical appliances. These have been simplified to 6 adults always present in the shelter as electricity supply in the camps has only happened at a later stage and still does not cover all the residents in every camp village (UNHCR 2018b).

Ventilation is provided through two pairs of 6-inch ventilation pipes, one at the top of each gable wall. The shelter can also ventilate through the front door and the 1 m² window in one of the side walls. Although the field survey raised issues with sand ingress through the ventilation pipes, and privacy issues with the location of the door and the window, here they are considered openable because the interest lies on the provision of natural ventilation opportunities and because residents do open windows nonetheless. These elements are modelled, together with infiltration, as a single-zone airflow network (Gu 2007). Due to limitations in the monitoring campaign, optimistic guesses were used to provide input data based on the literature: discharge coefficient of 0.7, airflow exponent of 0.65 and wind pressure coefficients by Swami and Chandra (ASHRAE 2017; CIBSE 2017; Swami and Chandra 1987; Orme, Liddament, and Wilson 1994). In addition, perfect window opening behaviour is assumed whenever is thermally advantageous and above 21 °C. Lastly, a minimum ventilation at 8 l·s⁻¹·p⁻¹ is always provided to ensure CO₂ levels are always kept below 1000 ppm. Although it is unlikely that this constant ventilation is achieved in practice, it constitutes a worst-case scenario for the severest overheating in this climate. As temperatures rise over 40 °C, it

might be best to reduce ventilation from an overheating point of view. Thus, this assumption hinders the performance of overheating mitigation measures.

3.2 *Human thermal models*

To quantify the impact of indoor overheating two models are used, one to assess comfort and one to assess heat strain. The first is the ASHRAE's adaptive comfort model (ANSI/ASHRAE 2016; de Dear, Brager, and Copper 1997). The model provides a temperature band T_{acm} that describes the temperature that most occupants would find comfortable in free running buildings (80% acceptability)

$$T_{acm} = 0.31 \cdot T_{pma} + 18.8 \pm 3.5 \quad (1)$$

where T_{pma} is the prevailing mean outdoor air temperature. Here, T_{pma} is taken as the exponentially weighted running mean of the daily mean outdoor air temperature to give more importance to recent thermal experiences (with $\alpha = 0.8$). In light of the social survey, it might seem that adaptation assumptions are not entirely satisfied as, for instance, female residents reported limited ability to adapt their clothing. Yet, it was also found that the thermal survey fitted well within this adaptive comfort model (Albadra et al. 2017).

The second approach is the Pierce 2-node model, a simplified representation of the heat transferences in the body (passive system) subject to the thermoregulatory control (active system) that adjusts physiological responses to the surrounding environment (Gagge, Fobelets, and Berglund 1986; Fountain and Huizenga 1997). This exposes the 'strain' the body is under to keep the heat balance with the environment, and it considers the influence of air and radiant temperatures, relative humidity, air velocity, activity level, work efficiency and clothing on a standardized individual. The first four variables are provided by the shelter simulation, with internal air speed

estimated through the time-varying natural ventilation air flow divided by the cross-section of the shelter unit. Activity level has been considered between 0.9 met and 1.1 met (night-time and daytime, respectively, no work being carried out) and clothing was taken as that of female residents, 0.93 ± 0.05 clo.

Among the many possible indicators and indices that can be derived from the Pierce 2-node model, the ‘discomfort index’ (DISC) is used to report heat strain. As noted by Gagge et al. (1986), this index measures the effort made by the body to restore comfort and, in the context of overheating, it measures the relative strain caused by the thermoregulatory sweating on a 5 point scale, with 0 describing comfortable conditions and 5 intolerable.

3.3 Evaluation method

The thermal indoor environment was evaluated with the following variables:

- 1) Mean indoor air temperature. Relative humidity is not included in this dry desert environment.
- 2) Mean surface temperature of walls. Interviewed residents reported that internal surfaces were often too hot to touch, being one of the reasons why many upgraded their shelters with additional internal insulation. The indicator here is the weighted average of wall surface temperatures because these are elements within residents’ reach.
- 3) Temperature difference between indoor operative temperatures and adaptive comfort model upper limit (ΔT). It is widely recognized that the acceptability of the indoor thermal environment is influenced, among others, by the duration and the severity of uncomfortable conditions outdoors (ANSI/ASHRAE 2016; BSI 2007). Although there is much debate in the literature on how to define overheating, standard guidelines define overheating as conditions where

temperatures surpass the adaptive comfort upper limit by more than 1 K for more than 1% of the occupied time or $\Delta T \geq 4$ K (CIBSE 2013; CIBSE 2017).

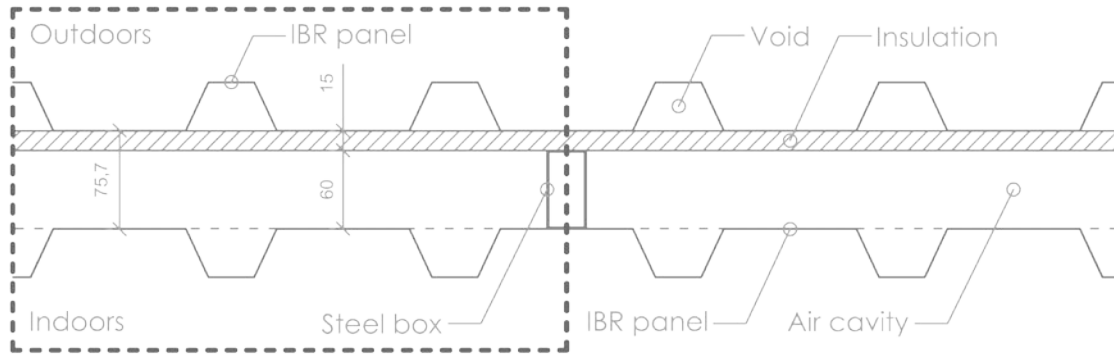
- 4) DISC votes in the Pierce 2-node model. Inspired in the previous limits of discomfort, it is assumed that votes of +3 or above in the DISC scale for more than 1% of the annual occupied time imposes excessive heat strain on the thermoregulatory system.

4 Current shelters: extrapolated thermal performance

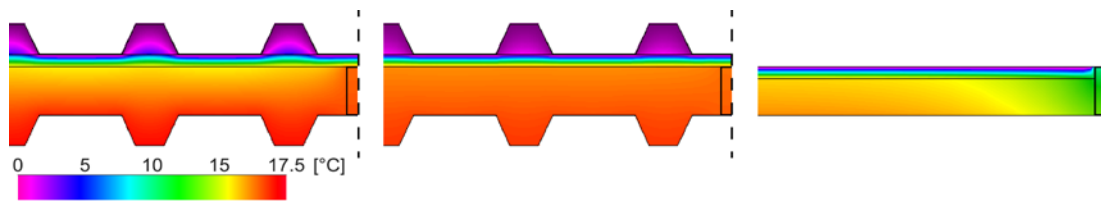
4.1 Base models and validation

Despite these shelters being all based on the same design and having relatively few number of design features, no two shelters are identical. Between-shelter variability and uncertainties were broadly constrained to ventilation, orientation and thermal resistance of constructions. Occupancy was deemed to not vary as overheating typically occurs during peak daytime, at which time the shelters are usually fully occupied.

Focusing on the latter as an example, inspections revealed that insulation was often squashed, loose, by-passed or covered in dust. This is assumed to differ from the likely design intent (Figure 2-a). The influence on thermal conditions is illustrated in thermal bridge analyses (Figure 2-b). Just the overall 2D thermal resistances range 0.63–0.5 times what simple calculations show under different assumptions of surface emissivity, air cavity thermal resistance and position of insulation.



a) Wall description (dimensions in mm; dashed rectangle indicates Figure 2-b view extent)



b) 2D Thermal bridge analyses of three scenarios: ‘best-case scenario’ (left), ‘best-case implementation’ (centre) and ‘assessed scenario’ (right) (boundary conditions $T_{\text{out}}=0\text{ }^{\circ}\text{C}$, $T_{\text{int}}=20\text{ }^{\circ}\text{C}$; see description in Figure 2-a; simulation software Therm (Huizenga et al. 2017))

Figure 2: Horizontal section through a typical wall support (see interlocking steel box structure arrangement in Figure 1)

To capture the expected variability, 32 model variants attempt to bound the performance of current shelters (low and high estimates of insulation thickness, air cavity resistance and emissivity of surfaces, ventilation effectiveness and infiltration, Table 1). The air temperature spot measurements of different shelters were combined into a single time series and split into two groups, one to calibrate the model and another one to validate it. The goodness of fit was evaluated in the validation group for every model (Figure 3). Considering the between-shelter variability, the uncertainties and limitations involved, as well as the coverage of monitored ranges, these results were regarded as sufficiently accurate for the purposes of this study.

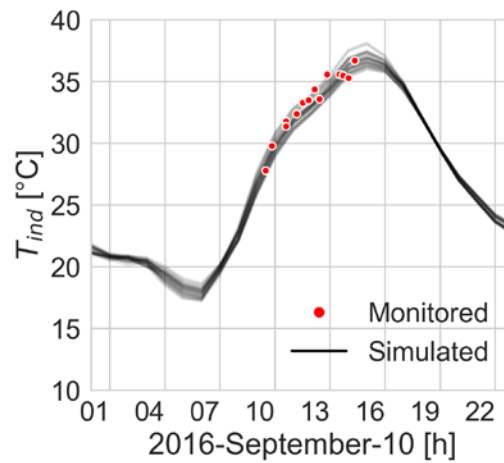


Figure 3: Current shelters: monitored indoor conditions (n=14) and simulated models (n=32) over 24 hours (average mean normalized error 4.4%, average root mean squared error 1.49 K)

4.2 Performance

The results are presented in Figure 4 for extrapolated annual overheating in current shelters, under typical weather conditions in Safawi. Although shelters do have heating, metrics are reported for free-running variants to expose their baseline performance.

Indoor air temperatures span a wide range, with minimums at 5 °C in the winter and maximums under 45 °C in the summer across all variants (Figure 4-a). Unsurprisingly, given the lightweight construction and little thermal insulation, the overview of indoor air temperatures follows closely the external ones, except for moderately warmer conditions in the cold season due to occupancy gains. Contrarily to extreme values, results obtained for the median and quantiles 0.25 and 0.75 show that, for nearly 50% of the time, indoor air temperature is within the comfort zone of 17.2 °C and 28.4 °C established by Albadra et al. (2017).

The acceptability of the indoor environment is also determined by the surface temperature of its enclosing elements. Ignoring for the moment the temperature of the radiant environment as a whole, which is accounted for in the human thermal models, results for the average wall surface temperature follow the patterns for air temperature.

The only noteworthy difference is that extreme values show greater variability across model variants due to the different thermal resistances of the walls. Numerically, the median of the maximums is 43.85 °C, in the 42 °C to 44.5 °C range where onset of contact pain is generally considered to take place (Ungar and Stroud 2010), which aligns with residents' testimonies. Note that the onset of contact pain is a function of the time of contact and thermal properties of the materials. The model by Ungar & Strout (2010) approach their threshold of 44 °C for contacts with aluminium objects (which is used in the shelter's IBR panel) for longer than 30 seconds.

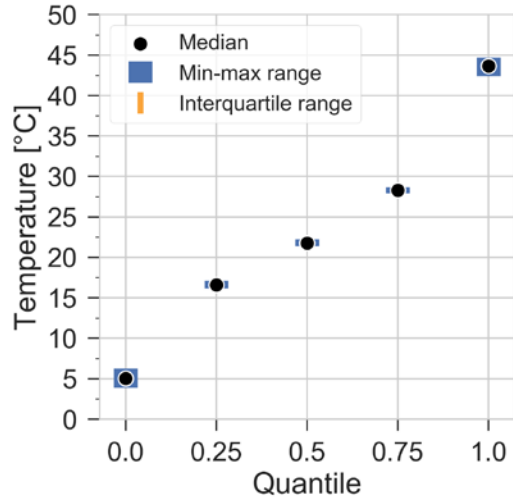
Results for the adaptive thermal comfort, based on the operative temperature index (calculated as per ISO 7726 (BSI 2002)), display large deviations from comfort (Figure 4-c). Note that Figure 4 shows the various subgroups discretized in 'bins' to separate the results. Here, bins represent normalized value counts of a variable. For example, the bin $[4, \infty)$ for ΔT reads 8%, which means that the upper limit of adaptive thermal comfort is surpassed by 4 K or more 8% of the time. Since shelters are considered here constantly occupied and evaluated over a non-leap year, this reads as

$$\frac{8}{100} \cdot 8760 \frac{\text{hours}}{\text{year}} = 700.8 \frac{\text{hours}}{\text{year}}.$$

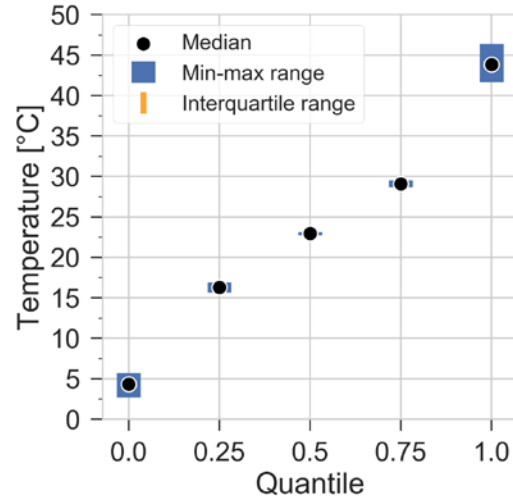
The cumulative annual overheating ranges between 16% and 21%, greatly surpass every recommended threshold. More worryingly, the breakdown reveals that the vast majority of this overheating happens in the severest bin¹ considered, $[4, \infty)$. Values in this bin exhibit a wider variability than their counterparts in the other indicators, suggesting a certain sensitivity to model assumptions.

The heat strain indicator further depicts an unacceptable indoor environment from the physiological perspective, with an annual cumulative average between 29%

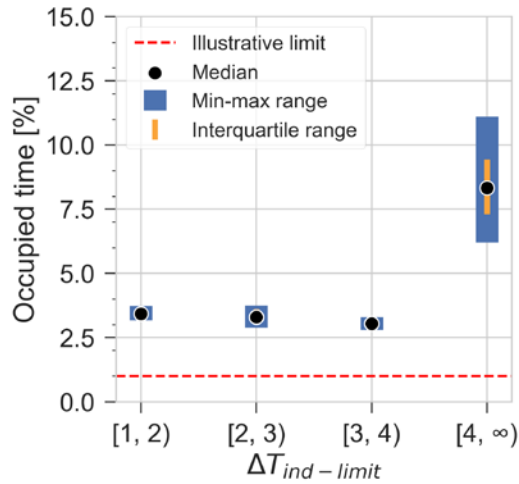
and 32% (Figure 3-d). Unlike in the adaptive comfort evaluation, results follow a diminishing progression at greater strains. Yet, minimum values in the $[3, \infty)$ bin are still above the selected illustrative limit.



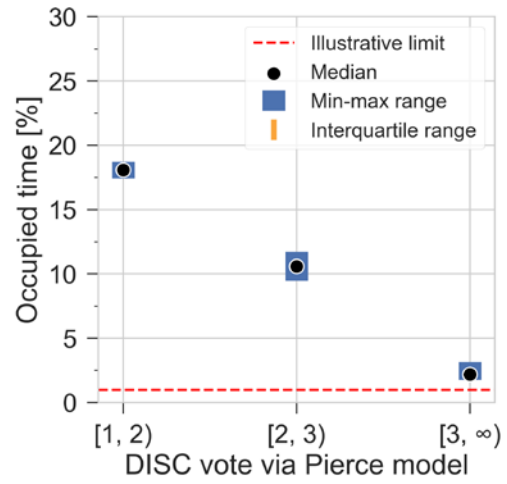
a) Indoor air temperatures



b) Indoor wall surface average temperatures



c) Annual overheating according to adaptive comfort model (n.b. Y-axis scale)



d) Annual heat strain according to the Pierce 2-node DISC indicator (n.b. Y-axis scale)

Figure 4: Current shelters: extrapolated conditions in free-running shelter variants (n=32 in each quantile or bin)

5 Design improvements: the role of passive architecture

5.1 Design brief

A parametric approach was adopted to assess every combination of the selected passive design strategies since the physical processes they control are tightly related. Equally important, this exposes estimates of performance robustness, as some measures might yield significant benefits if and only if others are present.

Table 1: Parametric design (starred cases correspond to bound estimates for current shelters in Section 4.1)

Parameter	Description
Orientation	Cases: {North*, West, South*, East} Notes: Orientation with respect to the façade with the window.
Insulation	Cases: {0.75*, 1.5*, 3, 6, 12} cm Notes: Insulation thickness for both walls and roof.
Construction	Cases: {original ideal*, original assessed*, sand in the 6 cm cavity, 36 cm sandbags, 12cm bricks} Notes: Constructions for the walls.
Shading	Cases: {current shading*, full shading of the whole shelter} Notes: Windspeed around shelter is the same in both cases.
Ventilation	Cases: {daytime, night time, day and night*} Notes: This refer to availability of the window and the door.
Infiltration	Cases: {1.5*, 2.3*} ach
Opening size	Cases: {1*, 1/2*, 1/4, 1/8, 1/16, 1/32} Notes: Cases are multipliers over ‘as-designed’ openable areas.
Heating	Cases: {available*, not available} Notes: Allows appraisal of free-running conditions and heating demand.
Total	14,400

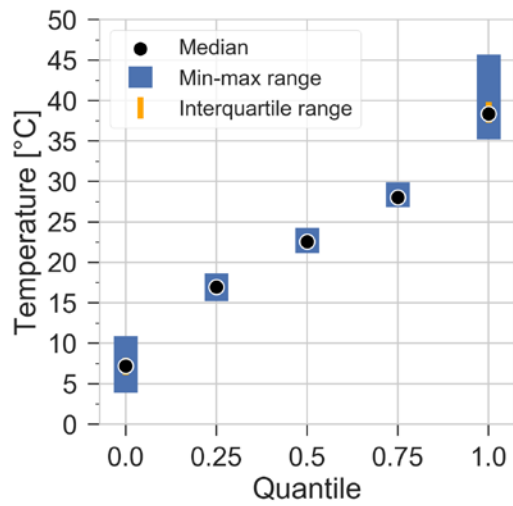
5.2 Performance

Figure 5 shows the results for the 7,200 free-running combinations of every parameter-case. Compared to the current shelters baseline in Figure 4-a, the main change in indoor air temperatures is a greater minimum-maximum range in every quantile, especially for the extreme ones (Figure 5-a). Although coldest and hottest temperatures are the same, — model variants do include those of Section 4 —, passive

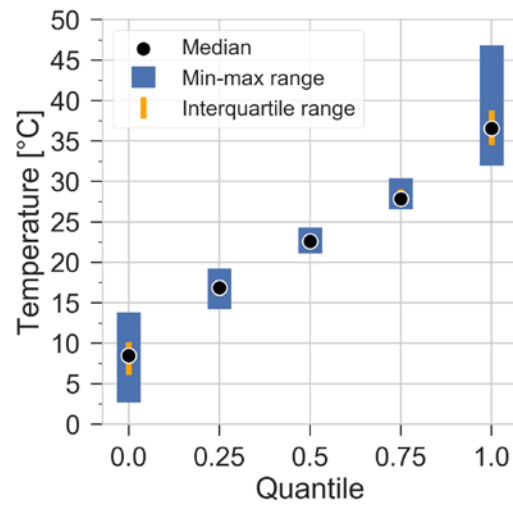
strategies can deliver minimum temperatures above 10 °C and maximum ones under 36 °C in the best-case scenarios. Still, the interquartile range of minimums and maximums temperature is just of a few degrees, indicating that this moderation in extreme temperatures is consistent for 50% of all these models. Wall surface average temperatures follow similar trends, with even greater moderation of extreme temperatures (Figure 5-b).

The cumulative annual overheating according to the adaptive comfort model ranges from nearly 0% to 23% (Figure 5-c). The key benefit of these passive strategies alternatives is clearly shown for the severest overheating: the median values for the bin $[4, \infty)$ are reduced from 8% in current shelters to nearly 0%. It must also be noted that maximum values here increased from 11% to more than 13%, indicating that a small proportion of strategies are counter-productive. Results in remaining bins depict further decreases in median overheating, with interquartile ranges featuring a wide range given the migration of the severest overheating to these categories.

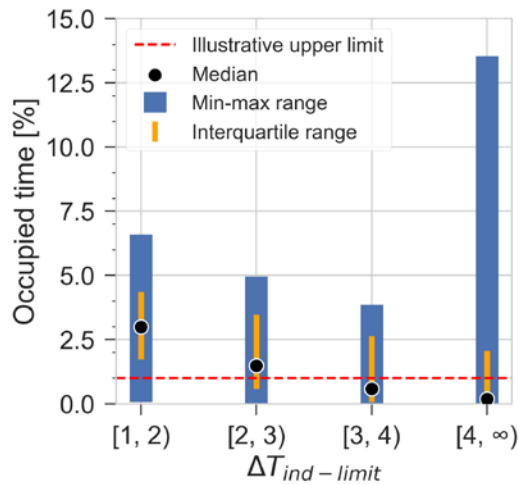
Lastly, results for the heat strain indicator follow analogous improvements to those obtained in the adaptive comfort model. The median for the bin $[3, \infty)$ is below the illustrative 1% limit, with its interquartile range just surpassing this threshold. Here too a small number of combinations can exacerbate overheating, with a maximum increase of +5% for the severest category assessed. Despite these benefits, female residents are still considered to vote $DISC \geq 1$ for more than 24% of the time.



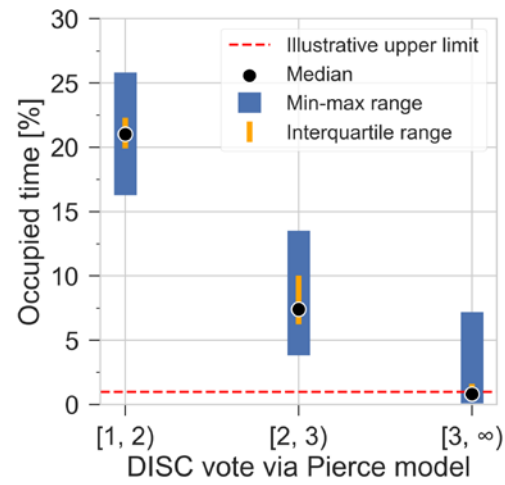
a) Indoor air temperatures



b) Indoor wall surface average temperatures



c) Annual overheating summary according to adaptive comfort model



d) Annual heat strain according to the Pierce 2-node DISC indicator

Figure 5: Design improvements: extrapolated conditions in free-running shelter variants (n = 7,200 in each quantile or bin)

Having proved the extent to which shelter variants can mitigate overheating, the question now becomes how parameters and cases in Table 1 contribute to the results. This is approached showing how overheating changes keeping constant one parameter-case at a time (i.e. the ‘main effects’, provided for overheating under the adaptive comfort model, Figure 6). Three parameters stand out:

- a) Shading: Blocking completely solar radiation is the single most powerful measure, capable of mitigating maximum overheating levels to under 8%. Although this is a theoretical scenario, this illustrates great potential for measures such as exterior ventilated air cavities.
- b) Insulation: Increasing insulation thickness proves to be second best in moderating maximum overheating levels.
- c) Thermal mass: As noted in the climate overview, comfortable temperatures can often be met at some point over the day all year round. Thermal mass can take advantage of this by dampening extreme temperatures and delaying their influence in the internal environment. However, this measure alone cannot guarantee meaningful changes in performance, as all thermal mass cases score maximum values above 20%. Still, only medium to heavyweight solutions can reduce annual overheating under 1%.

Overheating performance of the other parameters is highly conditional on the context set up by the three main variables, as hinted by their value distributions. For example, there is real value in providing large ventilation openings or opening windows during cooler parts of the day, night and year, even in lightweight, poorly insulated shelters of this size. Further work is needed on this subject.

The heating demand of the shelters could not be investigated in the field work (i.e. constant heating to a set point, regardless of the fuel available). Hence, it is estimated with shelter simulation variants. Although absolute values are reported, the interest is in the relative change of performance from the heating demand obtained for current shelters (those cases reported in Section 5 but with heating available). The median heating demand of these reference shelters is $89.20 \text{ kWh}\cdot\text{m}^{-2}$, with a standard deviation of $13.82 \text{ kWh}\cdot\text{m}^{-2}$. In contrast, median heating demand across all 7,200 cases

is $50.89 \text{ kWh}\cdot\text{m}^{-2}$, with a standard deviation of $21.14 \text{ kWh}\cdot\text{m}^{-2}$. Not only do these passive strategies mitigate overheating but they also reduce the heating demand. This could potentially improve indoor environment acceptability in winter, saving operational costs of the camp.

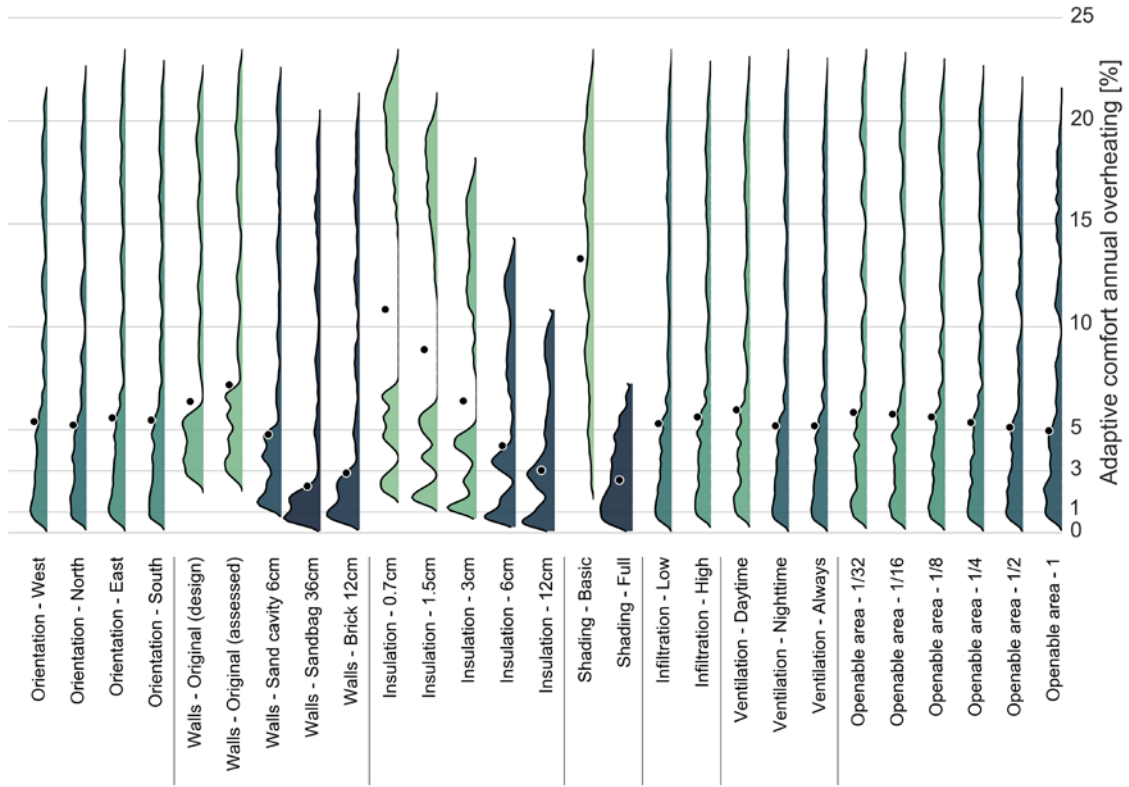
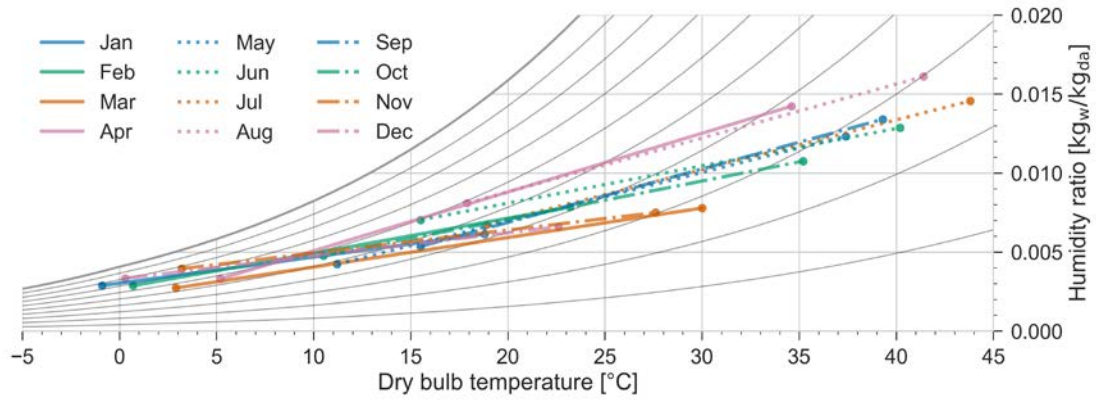
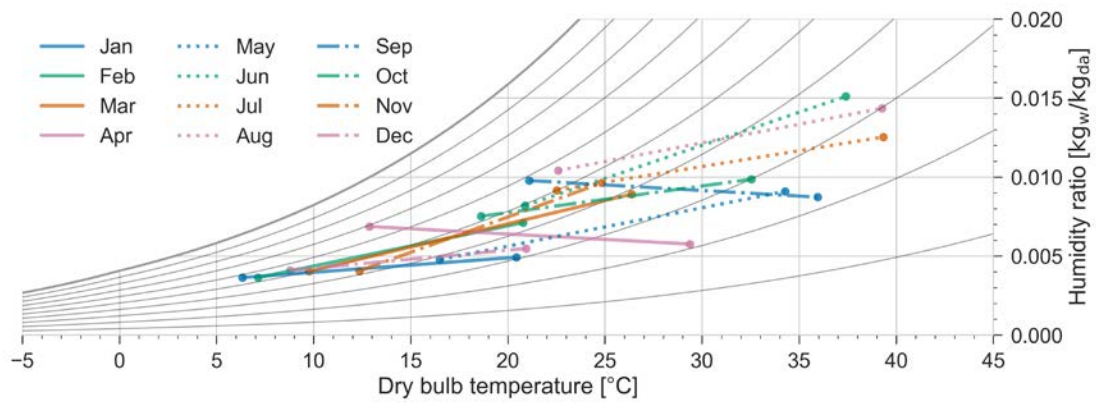


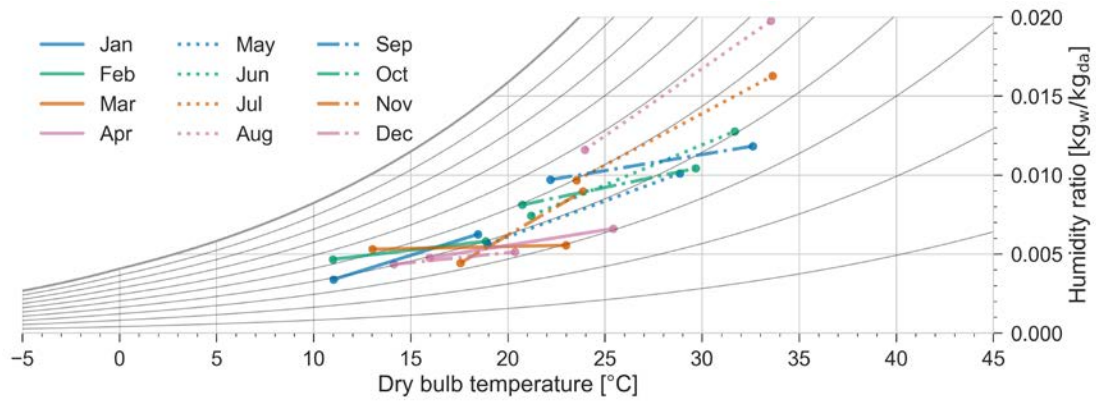
Figure 6: Distribution of annual overheating according to the adaptive comfort model in shelter proposals grouped by parameters and cases ($n_{unique} = 7,200$; dot and density shade colour indicate the median)



a) Climate description based on typical year weather file (see Section 2.1; range selection based on monthly minimum and maximum temperatures)



b) Overview of free-running version of original shelters (see Section 4; ranges based on the 5th and 95th percentile of indoor air temperatures)



c) Free-running shelter proposals with lowest annual overheating duration (see Section 5; ranges based on the 5th and 95th percentiles of indoor air temperatures)

Figure 7: Psychrometric chart summaries ($p_{atm} = 93,978$ Pa, i.e. mean atmospheric pressure at location; ranges based on two sample points per month)

6 Discussion

Figure 7 shows a summary overview of the extent to which passive architecture, through a cyclical process of design improvements, can enhance thermal living conditions in the shelter. The climate and environmental conditions at the study camp are severe, resulting in large deviations from generally accepted comfort norms throughout the year (Figure 7-a). These conditions in turn are transmitted to the indoor space in the current shelters since they fail to moderate heat transfer (Figure 7-b). In contrast to this, we demonstrate that carefully designed shelters can take advantage of the external environment to actively promote an internal environment that is significantly closer to comfort (Figure 7-c), with even the limited number of strategies considered here.

The measures shown in Table 1 could be materialised in several ways and create a compelling case for the approach. However, there is still the need to consider other elements of camp life. For example, efforts to provide cross ventilation with an increased number of windows would be a poor choice if privacy and security concerns of the residents are not addressed.

6.1 Limitations and challenges in overheating simulation

This work highlights the potential benefits of cyclic design in shelter provision. Like all modelling work, there are limitations to the accuracy of the results, arising from the limitations of the simulation model used, for example here in the airflows and heat exchanges within the envelope cavities and also by the impossibility of predicting how interventions will be used by occupants. The model does not deal well with issues of natural ventilation or energy storage in the system and further work needs to be done to

optimise the potential for comfort cooling and heating in the structures using these strategies.

Finally, despite the fact that the limits of discomfort and heat stress are widely used, we can only treat them as educated guesses of the actual limits of discomfort and heat stress since these are typically based on healthy adults in very different climates, many developed purely for *male* adults in the military or mining industries. Hence, how they relate to children, women and the elderly in these shelters is unknown.

7 Conclusions

The provision of adequate shelter for refugees is becoming a globally pressing issue. Understandably, thermal conditions are not initially a primary concern when housing large number of individuals as a response to a humanitarian crisis. However, as the lifetime of camps is extended, the quality of indoor environments is expected to become of greater interest to ensure the well-being of residents.

Since the thermal performance of structures is deeply affected by their design, it is tempting to assume that shelters need to be rethought from the ground up. However, considering the established dynamics behind refugee housing provision, this approach is likely to ignore the lessons learned in broader aspects of shelter design. Instead, taking advantage of the ‘planned temporariness’ of shelters, we have explored the potential for a ‘cyclic design approach’, a way of building up on top of current solutions to improve shortcomings in their performance while retaining their proven advantages.

This cyclic design approach was demonstrated in the Azraq refugee camp in Jordan. Validated simulations models and on-site measurements showed that the current transitional shelters of this camp overheat causing both discomfort and at times heat stress. Based on these findings simulated modifications to the shelters incorporating a

range of simple passive design improvements resulted in significant performance improvements, even completely removing the severest overheating incidences in some cases.

The lack of a regulatory framework regarding the thermal performance of refugee shelters results in a general acceptance of the existence of low levels of comfort and high levels of thermal stress inside such temporary camps. That shelters are a temporary housing solution, need not mean the global community should acquiesce to this. Furthermore, it is clear from the field surveys that shelter designs need to be sensitive to the background and cultures of camp residents if the shelters are to be a humane and sustainable solution during their lifetime.

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Data Access Statement

Dataset in this study is openly available at <https://doi.org/10.15125/BATH-00424>.

ORCID

Daniel Fosas <https://orcid.org/0000-0001-8407-3431>

Dima Albadra <https://orcid.org/0000-0001-5274-0834>

Sukumar Natarajan <https://orcid.org/0000-0001-5831-1678>

David A. Coley <https://orcid.org/0000-0001-5744-1809>

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